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MEASUREMENT OF STRONTIUM-89 AND STRONTIUM-90 IN ENVIRONMENTAL WATERS. A TENTATIVE REFERENCE METHOD

Environmental Monitoring and Support Laboratory
Las Vegas, Nevada

March 1976

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16. ABSTRACT

A tentative reference method for the measurement of strontium-89 and -90 in environmental waters is described. Samples of environmental water sources are collected, preserved with acid-strontium carrier, and analyzed for strontium-89 and/or strontium-90. Strontium-89 and -90 are separated from the sample water by precipitating with stable strontium carrier as carbonate. The strontium carbonate is dissolved, yttrium-90 separated, the strontium reprecipitated as carbonate, filtered, and counted for the combined strontium-89 and -90 activity. The yttrium-90 is allowed to grow in from the strontium-90 activity; the strontium carbonate is redissolved; the yttrium-90 is separated, precipitated, and counted for the strontium-90 determination. The strontium-89 activity is then determined by difference of the total strontium-89 and -90 and the separate strontium-90 activities. Recoveries are determined from the added and found (recovered) strontium carrier. Counting efficiencies are determined with prepared standard reference samples. Results are reported in pCi/liter.

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MEASUREMENT OF STRONTIUM-89 AND STRONTIUM-90 IN ENVIRONMENTAL WATERS

A Tentative Reference Method

by

Quality Assurance Branch
Monitoring Systems Research and Development Division
Environmental Monitoring and Support Laboratory
Las Vegas, Nevada 89114

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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TENTATIVE REFERENCE METHOD FOR THE MEASUREMENT OF STRONTIUM-89 AND STRONTIUM-90 IN ENVIRONMENTAL WATERS

1. Principle and Applicability

A known amount of inactive strontium ions, in the form of strontium nitrate, is added to the sample as a "carrier" to determine percent of recovery. The strontium, both carrier and radionuclide, is separated from other radioactive elements and sample solids by precipitation as strontium nitrate from fuming nitric acid solution. The strontium carrier and radionuclides are then precipitated as strontium carbonate, dried, weighed to determine recovery of carrier, and the radioactivity determined. The radioactivity counted is normalized to 100 percent recovery by using the recovery factor.

It is impossible to separate the isotopes strontium-89 and strontium-90 by chemical procedure; therefore, the amount of strontium-90 is determined by separating and counting the activity of its daughter, yttrium-90. At equilibrium, the activity of yttrium-90 and strontium-90 are equal. The strontium-89 is then determined by difference.

This method is applicable to measuring radioactive strontium-89 and 90 or only strontium-90 in drinking water or in filtered raw water. It is also applicable to sewage and industrial wastes, provided steps are taken to destroy organic matter and eliminate other interfering ions.

2. Range and Sensitivity

The minimum limit of concentration to which this method is applicable will depend on sample size, counting efficiency, background, and counting time. Since radioactivity decay is random rather than uniform in nature, it is necessary to count the decay emissions (in this case, beta particles) sufficiently long to obtain the desired statistical reliability. It is recommended that samples be counted long enough so that samples with strontium-89 and/or strontium-90 activities as low as the detection limit of the method and the counting instrument used will have a counting error no greater than the sample net count rate (when counting error counts per minute (cpm) equals sample net cpm, the counting error is 100 percent). For instance, when a 1-liter water sample is analyzed for strontium-90 by this method and is counted for 20 minutes in a low background beta counting system (2 cpm background), with a counting efficiency of 41 percent, and a gross count rate of 3 cpm is obtained, the sample will have a net count rate of 1 cpm and a counting error of plus or minus (±) 1 cpm at the 95 percent confidence level. This corresponds to a detection limit of 1 ± 1 pCi/liter. Samples having higher concentrations and counted for the same time (20 minutes) will have correspondingly lower counting errors.

The range of the method is 1 pCi/liter to 10^4 pCi/liter for 1-liter sample size. Smaller aliquots should be analyzed for strontium-89 and 90 activities above 10^4 pCi to avoid counting instrument resolution losses.

3. Interferences

Radioactive barium will precipitate with radioactive strontium. Stable barium is added to the sample and then steps are included in the method that separates barium from strontium. Radium isotopes are also removed with the barium.

Samples that naturally contain significant amounts of stable strontium will cause errors in the recovery of the added strontium carrier. Blank samples to which no strontium carrier is added should be run to determine natural strontium content. Hard waters contain calcium which precipitates with the strontium in the initial carbonate precipitation. If not separated, the calcium will cause errors in the recovery of the strontium carrier. This method includes steps to remove calcium from the sample.

4. Precision and Accuracy

Water samples containing 10, 100, and 1000 pCi/liter of both strontium-89 and 90 can be analyzed for each radioisotope with a precision of less than ± 25 percent, ± 15 percent, and ± 10 percent respectively at the 95 percent confidence level. The overall accuracy is a combination of the accuracy of the standard used and the precision and accuracy of the measurement procedure. Using this method, analysis of water samples containing as little as 10 pCi each of strontium-89 and 90 should be accurate within ± 25 percent at the 95 percent confidence level. The method is slightly biased on the low side.

5. Apparatus

Low background beta counting system (A thin-window proportional or Geiger-Müller counter, 2-inch diameter or more window, with not more than 3 cpm background on the beta voltage plateau, is recommended.)

Stainless steel planchets, 2-inch diameter by 1/4-inch deep

47-mm diameter glass fiber and 0.45-micrometer pore membrane filters (cellulose triacetate type)

Filter holder, 2-liter filter flask, and stopper adapter

Centrifuge and 50-milliliter (ml) centrifuge tubes

Separatory funnels, 60-ml

Drying oven

Desiccator and desiccant

Sintered-glass (fine) crucibles

Beakers: 250-ml, 400-ml, 2000-ml

Graduated cylinders: 50-ml, 100-ml, 1000-ml, 4000-ml

Hot water bath

6. Reagents. All chemicals should be of "reagent-grade" or equivalent whenever they are commercially available.*

Strontium carrier (10 mg/ml): Dissolve and dilute 24.16 grams (g) of $Sr(NO_3)_2$ to 1 liter in a volumetric flask with distilled water. Thoroughly mix and standardize as follows: Carefully pipet three 10.0-ml portions of the carrier solution into separate 50-ml centrifuge tubes. Add 15 ml of 2N Na_2CO_3 solution (see sodium carbonate solution below) and stir. Heat in a boiling water bath for 15 to 20 minutes. Allow to cool and filter out the $SrCO_3$ precipitate in a tared sintered-glass (fine) crucible. Wash the precipitate and the crucible walls with three 5-ml distilled water portions adjusted to pH 8

* "Reagent Chemicals, American Chemical Society Specifications," American Chemical Society (ACS), Washington, DC. For reagents not listed by the ACS see "Reagent Chemicals and Standards" by Joseph Rosin, D. Van Nostrand Company, Inc., New York, NY, or the "United States Pharmacopeia" for purity tests.

with NH_4OH, and with three 5-ml portions of acetone. Dry the crucible for 30 minutes in a 100° C oven. Cool the crucibles in a desiccator and weigh.

Calculations:

$$\text{Strontium, mg/ml} = \frac{\text{mg of } SrCO_3 \times 0.5935}{10 \text{ ml}}$$

Yttrium carrier (10 mg/ml): Dissolve and dilute 43 g of $Y(NO_3)_3 \cdot 6H_2O$ plus 5 ml of concentrated nitric acid to 1 liter in a volumetric flask with distilled water. Standardize the carrier solutions by the following procedure: Carefully pipet three 10.0-ml portions of the carrier solution to separate 50-ml centrifuge tubes. Add 40 ml of saturated ammonium oxalate solution to each centrifuge tube and stir. Heat in a hot water bath (near boiling) for 30 minutes. Cool in an ice bath. Filter the precipitates into a tared sintered-glass (fine) crucible. Wash the crucible walls and the precipitate with three 5-ml portions of distilled water, then with three 5-ml portions of ethyl alcohol, and finally with three 5-ml portions of acetone. Air dry the crucibles for 1 hour or longer and weigh.

Calculations:

$$Y/Y_2(C_2O_4)_3 \cdot 9H_2O = 88.92/604.05 = 0.1472$$

$$\text{Yttrium, mg/ml} = \frac{\text{mg of } Y_2(C_2O_4)_3 \cdot 9H_2O \times 0.1472}{10 \text{ ml}}$$

Barium carrier: Dissolve and dilute 19.0 g of $Ba(NO_3)_2$ with distilled water to 1 liter (10 mg Ba/ml).

Ammonium hydroxide, 0.1N (1 volume of concentrated NH_4OH diluted with 150 volumes of distilled water)

Ammonium oxalate, saturated solution: Add enough $(NH_4)_2C_2O_4 \cdot H_2O$ to distilled water so that crystals persist (8 gm/100 ml).

Ammonium acetate buffer solution: Dissolve 154 g of $NH_4C_2H_3O_2$ in 800 ml of distilled water, add 57 ml of glacial acetic acid, adjust the mixture to pH 5.5 using glacial acetic or concentrated NH_4OH as needed. Dilute to 1 liter.

Acetic acid (1+2): Mix 1 volume of glacial acetic acid with 2 volumes of distilled water.

Ammonium hydroxide, concentrated (specific gravity 0.90)

Nitric acid, fuming (90%)

Nitric acid, concentrated (70%)

Sodium carbonate solution: Dissolve and dilute 124 g of $Na_2CO_3 \cdot H_2O$ (or 106 g of Na_2CO_3) with distilled water to 1 liter (2N solution).

Sodium chromate solution: Dissolve and dilute 117 g of $Na_2CrO_4 \cdot 4H_2O$ with distilled water to 1 liter (0.5M solution).

Sodium hydroxide solution: Dissolve and dilute 240 g of NaOH with distilled water to 1 liter (6N).

Tributyl phosphate, reagent-grade: Wash by shaking with an equal volume of 14N nitric acid. Discard the washings.

Methyl red indicator: Dissolve and dilute 0.1 g of methyl red to 100 ml with distilled water.

Acid-carrier solution for preservation of samples: To a 1-liter volumetric flask add 3.86 g of $Sr(NO_3)_2$ and 3.04 g of $Ba(NO_3)_2$, add 400 ml of distilled water

and 500 ml of concentrated HNO_3, swirl the flask to mix the contents, cool the solution to room temperature, dilute to volume with distilled water, and mix thoroughly. For sample preservation in the field, transfer 50.0-ml portions of the solution to 2-ounce polyethylene bottles, and cap with poly-seal caps. This acid-carrier solution should not be stored in the polyethylene bottles for more than a few days. 50.0 ml of the solution contains 80 mg each of strontium and barium carriers.

7. Procedures

7.1 Sampling

Sampling is described in "Environmental Radioactivity Surveillance Guide," published by the U.S. Environmental Protection Agency as report ORP/SID 72-2. It is recommended that samples be preserved at the time of collection by the addition of 50 ml of 8N nitric acid containing 80.0 mg each of strontium and barium carriers per 4 liters (or 1 gallon) of sample collected. However, if determination is to be made of the strontium-89 and 90 content in the separate dissolved and suspended fractions of the sample, then those fractions must be separated before the preservative is added, since the preservative may change the distribution of the sample radioactivity. Rather than separating the dissolved and suspended solids fractions in the field, samples can be brought to the laboratory without preservative added and those samples should be so labeled. Separation is then done by filtering out the suspended solids on a weighed 0.45-micrometer pore membrane filter. The filter is dried, weighed, and set aside for further analysis. The preservation solution is then added to the filtrate which is returned to the original sample container and held there for overnight or longer before analysis is begun.

Note: Samples brought in without preservative added (because dissolved and suspended fractions are to be separated) may not remain completely unchanged as to their fractional radioactivities. Container wall effects and temperature change could result in a change in the radioactivity concentrations of the two sample fractions. When such change is suspected, or when significant radioactivity is found in the suspended solids fraction, then another sample should be taken and separation of the two fractions done in the field.

7.2 Analysis

7.2.1 Strontium-89 and Strontium-90

7.2.1.1 All samples to which have been added acid-carrier preservative, and whose volumes have not been measured, should now be measured so that accurate carrier concentrations can be determined. This is required for later yield determinations. Sample aliquots should be corrected for the acid-carrier dilution.

For suspended solids fractions that are to be analyzed separately, transfer the filter holding the suspended solids to a 250-ml beaker. Add 2.0 ml each of strontium, yttrium, and barium carriers. Wet-ash the filter and suspended solids with one or more treatments of 20 ml of concentrated nitric acid plus 2 ml of 30 percent hydrogen peroxide, evaporating to near dryness with each treatment. Wet-ash until there is little or no color, or no added color change in the evaporated solids. Dissolve and dilute the residue to 200 ml using 10 ml of 70 percent nitric acid and 180 ml of distilled water. Filter the solution through a 0.45-micrometer membrane filter and rinse with two 25-ml portions of distilled water, adding the rinses to the filtrate. Discard the filter. This sample fraction is now ready to treat with the steps that follow.

7.2.1.2 Transfer 1-liter water sample aliquots to 2-liter beakers, and the suspended solids wet-ashed solutions to 400-ml beakers. Heat the samples to boiling and add 80 ml of 6N NaOH, stir, and add 50 ml of 2N Na_2CO_3 solution. Continue heating to near boiling for 1 hour with occasional stirring. Then set the beakers aside for at least 2 hours, allowing the carbonate precipitate to settle.

7.2.1.3 Decant most of the clear supernate and discard it. With the remainder of the supernate and necessary water washes (adjusted to pH 8 with NH_4OH), quantitatively transfer the precipitate to a 50-ml centrifuge tube. Centrifuge at 2000 revolutions per minute (rpm) for 10 minutes and discard the supernate. This precipitate will contain the strontium and barium carriers.

7.2.1.4 Dissolve the precipitate by careful dropwise addition of 4 ml of concentrated nitric acid, heat in a boiling water bath for about 20 minutes with occasional stirring. Cool the centrifuge tube and contents with cold tap water.

7.2.1.5 Add 20 ml of fuming nitric acid to the centrifuge tube, cool in an ice bath and stir. Centrifuge at 2000 rpm for 10 minutes, and discard the supernate. Supernate will contain sample calcium.

7.2.1.6 Add 4 ml of water to the precipitate, heat in a hot water bath with occasional stirring to dissolve. Then repeat step 5.

7.2.1.7 Dissolve the strontium and barium nitrate precipitate in 25 ml of water, add 2 drops of methyl red indicator solution, neutralize to yellow color with NH_4OH, then adjust the pH back to red color by adding dropwise (1+2) acetic acid.

7.2.1.8 Add 5 ml of the ammonium acetate buffer solution. Heat in a hot water bath. Add, with stirring, 2 ml of the 0.5M Na_2CrO_4 solution and digest in the hot water bath for 15 minutes. Cool the reaction mixture and centrifuge at 2000 rpm for 10 minutes. Transfer the supernate to a clean 50-ml centrifuge tube, and discard the barium chromate residue (or save for radioactive barium, radium, or lead analysis).

7.2.1.9 To the buffered chromate supernate add 2 ml of concentrated NH_4OH; heat in a hot water bath; add 5 ml of 2N Na_2CO_3 solution; digest in the hot water bath for 15 minutes; cool; centrifuge, and discard the supernate.

7.2.1.10 In this step the strontium-89,90 is separated from yttrium-90 with a yttrium carrier scavenge to start a specific ingrowth period and to get a separate radiostrontium count in the following steps. Add a few drops of concentrated HNO_3 to the carbonate precipitate; add 15 ml of water; add 1 ml of the yttrium carrier solution; add 1 drop of wetting agent solution (such as "Photo-Flo," an Eastman Kodak Company film processing product); add 5 ml of concentrated HN_4OH; heat in a hot water bath for 15 minutes with occasional stirring. Centrifuge and transfer the supernate to a clean 50-ml centrifuge tube. Wash the yttrium hydroxide precipitate with 5 ml of water, centrifuge and add this wash to the supernate. Note the time of this yttrium hydroxide precipitation which marks the beginning of the yttrium-90 ingrowth period. From this point on it is important to proceed without delay to the final separation and count of the strontium-89 and 90 activity.

7.2.1.11 Add 5 ml of 2N Na_2CO_3 to the supernate from step 10, heat in a hot water bath for 15 minutes, cool in a cold water bath for about 10 minutes, centrifuge and discard the supernate.

7.2.1.12 Dissolve the strontium carbonate precipitate with a minimum amount of (1+5) nitric acid dropwise. Add 20 ml of water, 1 ml of concentrated NH_4OH, and 2 ml of 2N $NaCO_3$ solution. Heat in a hot water bath for 15 minutes, cool for 10 minutes.

7.2.1.13 Transfer the strontium carbonate precipitate quantitatively to a tared glass fiber filter. Wash the precipitate with three 10-ml portions of water adjusted to pH 8 with NH_4OH, then with three 10-ml portions of acetone. During filtration and washes of the strontium carbonate, minimize the time of air flow through the filter to avoid collection of radon daughters. Dry the filter at 110° C for 10 minutes, then weigh and count (within 2 hours). This count gives the total of strontium-89 and 90 activities, plus the ingrown yttrium-90. Note the time of this count as it must be corrected for yttrium-90 ingrowth (time between steps 10 and 13).

7.2.2 Strontium-90 (By Yttrium-90)

7.2.2.1 After counting the strontium carbonate for strontium-89 and 90 activity, store the filter for a measured period of ingrowth and proceed with the following steps for yttrium-90 separation. A 2-week or longer ingrowth period is recommended for samples with very low strontium-90 activity. Step 7.2.1.10 was the beginning of this ingrowth period.

7.2.2.2 Transfer the filter to a small funnel which has been placed to drain into a 60-ml separatory funnel. Dissolve the strontium precipitate by carefully wetting the filter with 5 ml of 6N nitric acid. Wet the filter with 2.0 ml of the yttrium carrier solution. Then rinse the strontium and yttrium into the separatory funnel by washing the filter with four more 5-ml portions of 6N nitric acid.

7.2.2.3 Rinse the filter and funnel with 10 ml of fuming nitric acid, collecting the rinse in the separatory funnel. Swirl the separatory funnel to mix the solution contents.

7.2.2.4 Add 10 ml of the acid-washed tributyl phosphate, stopper, and shake thoroughly for 3 to 5 minutes. Allow the phases to separate and transfer the aqueous phase to a second 60-ml separatory funnel.

7.2.2.5 Add 10 ml of acid-washed tributyl phosphate to the second separatory funnel. Shake for 3 to 5 minutes, allow the phases to separate, transfer the aqueous phase to a third 60-ml separatory funnel.

7.2.2.6 Combine the two tributyl phosphate portions into one separatory funnel and wash twice with 5-ml portions of 14N HNO_3. Add these acid washes to the aqueous phase. The aqueous phase contains the strontium fraction and can be saved for a second ingrowth of yttrium-90 if so desired. Record this time as the beginning of the yttrium-90 decay.

7.2.2.7 Extract the yttrium from the tributyl phosphate by shaking for 3 to 5 minutes with 10 ml of 0.1N HNO_3. Transfer the 0.1N HNO_3 phase to a 50-ml centrifuge tube. Repeat the extraction with another 10-ml portion of 0.1N HNO_3 and add this extract to the centrifuge tube. Discard the tributyl phosphate phase.

7.2.2.8 Precipitate the yttrium as hydroxide by adding 10 ml of concentrated NH_4OH to the centrifuge tube, stirring and heating for 10 minutes in a hot water bath. Centrifuge at 2000 rpm for 10 minutes and discard the supernate. Wash the precipitate with two 10-ml 0.1N NH_4OH washes, centrifuging at 2000 rpm for ten minutes and discarding the washes.

7.2.2.9 Dissolve the precipitate in 15 ml of distilled water containing 2 ml of HCl (1+1). Precipitate the yttrium as oxalate by adding 20 ml of saturated ammonium oxalate solution; heat for 30 minutes in a hot water bath (near boiling). Cool in an ice bath and then filter the yttrium oxalate on a tared glass fiber filter. Wash the precipitate with three 5-ml portions of distilled water, then with three 5-ml portions of ethyl alcohol, and finally with three 5-ml portions of acetone. Air dry the filter for about 1 hour, then weigh and count for yttrium-90 activity. Record the time of the counting for decay correction (time between step 7.2.2.6 and count time).

8. Calibration

8.1 Counting Efficiencies

Separate counting efficiencies should be determined for strontium-89 and 90 using known amounts of the respective radioactivities and 20.0 mg of strontium carrier, precipitated as carbonate and counted. A strontium-90 precipitate is prepared after separation of the yttrium-90 daughter by the following procedure. Add a known amount of strontium-90 standard, in the order of 1000 disintegrations per minute (dpm), and 20 mg of strontium carrier to a 50-ml centrifuge tube, add 20 ml of water and proceed as in steps 7.2.1.10 through 7.2.1.13 but omitting step 7.2.1.12. Then for the yttrium-90 counting efficiency continue with steps 7.2.2.1 through 7.2.2.9.

9. Calculations and Reporting

9.1 Chemical Yields for Strontium and Yttrium

$$\text{Yield factor for Sr, a} = \frac{\text{mg } SrCO_3 \text{ recovered}}{\text{mg Sr carrier added (as carbonate)}}$$

20 mg of strontium is equivalent to 33.7 mg $SrCO_3$.

$$\text{Yield factor for Y, b} = \frac{\text{mg } Y_2(C_2O_4)_3 \cdot 9H_2O \text{ recovered}}{\text{mg Y carrier added (as oxalate)}}$$

9.2 Other Terms for Calculations

c = strontium-90 counting efficiency

d = strontium-89 counting efficiency

e = yttrium-90 counting efficiency

f = yttrium-90 decay factor

g = yttrium-90 ingrowth factor, for unwanted yttrium-90 in total strontium-89,90 count

h = strontium-89 decay factor

V = volume of sample analyzed, in liters

i = yttrium-90 ingrowth factor for strontium-90 by yttrium-90 determination

9.3 Calculations for Activities at Equilibrium Conditions

Cpm values indicated are net cpm (reagent blank, including background, subtracted).

$$\text{Y dpm} = \frac{^{90}\text{Y cpm}}{\text{abeff}} = {}^{90}\text{Sr dpm}$$

$$^{90}\text{Sr cpm} = {}^{90}\text{Y dpm} \times c$$

$$\text{Total } {}^{89,90}\text{Sr cpm} = \text{total cpm } (SrCO_3) - \text{ingrown } {}^{90}\text{Y cpm}$$

$$\text{Ingrown } {}^{90}\text{Y cpm} = {}^{90}\text{Sr dpm} \times e \times g$$

$$^{89}\text{Sr cpm} = \frac{\text{total Sr cpm}}{a} - {}^{90}\text{Sr cpm} - {}^{90}\text{Sr dpm} \times e \times g$$

$$^{89}\text{Sr dpm} = \frac{^{89}\text{Sr cpm}}{d}$$

$$^{90}\text{Sr pCi/liter} = \frac{^{90}\text{Sr dpm}}{2.22 \times V}$$

$$^{89}\text{Sr pCi/liter} = \frac{^{89}\text{Sr dpm}}{2.22 \times V}$$

Error associated with the results of the analysis should also be reported. See Appendix A for error and statistical calculations. See Appendix B and C for yttritum-90 decay and ingrowth factors, and Appendix D for strontium-89 decay factors.

APPENDIX A. ERROR AND STATISTICAL CALCULATIONS

Because of the random nature of radioactivity disintegrations there is an error associated with any measured count of these disintegrations. The variability of any measurement is indicated by the standard deviation. The standard deviation in the counting rate is determined by the following equation:

$$\sigma\,(R) = \left(\frac{R_o}{t_1} + \frac{B}{t_2}\right)^{\frac{1}{2}}$$

where R_o = gross count rate
t_1 = counting time for the gross count
B = background count rate
t_2 = counting time for the background count

Let $\sigma(R_1) = D_1$ = standard deviation for the count of total $^{89,90}Sr$ (from $SrCO_3$ precipitate, which includes the unwanted ingrown ^{90}Y)

Let $\sigma(R_2) = D_2$ = standard deviation for the ^{90}Y count for ^{90}Sr determination

The counting error for a given sample for the ^{89}Sr and ^{90}Sr determinations expressed in pCi/liter are shown as follows:

For ^{90}Sr, $E = \dfrac{1.96\ D_2 \times 1000}{2.22abefiV}$

For ^{89}Sr, $E = \dfrac{1.96 \times 1000}{2.22adV}\left[(D_1)^2 + \left(\dfrac{c + e \times g}{befi}\right)^2 (D_2)^2\right]^{\frac{1}{2}}$

where 1.96 = 95% confidence factor
1000 = ml/liter
2.22 = dpm/pCi
a = strontium recovery factor
b = yttrium recovery factor
c = ^{90}Sr counting efficiency
d = ^{89}Sr counting efficiency
e = ^{90}Y counting efficiency
f = ^{90}Y decay factor
g = ingrowth factor for unwanted ^{90}Y in total $^{89,90}Sr$ count
i = ingrowth factor for ^{90}Y for ^{90}Sr determination

These were derived by applying propagation of error theory to the expressions in Section 9.3.

The standard deviation of a number of experimental analyses or observations is determined by:

$$S_n = \left[\sum_{i=1}^{m} (n_i - \bar{n})^2/m - 1)\right]^{\frac{1}{2}}$$

where n_i = activity (pCi/liter of a given sample
$\bar{n}$ = mean activity (pCi/liter) of a series of analyses
m = the number of replicate analyses

APPENDIX B. YTTRIUM-90 DECAY AND INGROWTH FACTORS (0-72 HOURS)

t (hr)	$e^{-\lambda t}$	$1-e^{-\lambda t}$	t (hr)	$e^{-\lambda t}$	$1-e^{-\lambda t}$	t (hr)	$e^{-\lambda t}$	$1-e^{-\lambda t}$
0.0	1.0000	.0000	24.0	.7717	.2283	48.0	.5955	.4045
0.5	.9940	.0054	24.5	.7676	.2324	48.5	.5923	.4077
1.0	.9893	.0107	25.0	.7634	.2366	49.0	.5891	.4109
1.5	.9839	.0161	25.5	.7593	.2407	49.5	.5860	.4140
2.0	.9786	.0214	26.0	.7552	.2448	50.0	.5828	.4172
2.5	.9734	.0266	26.5	.7512	.2488	50.5	.5797	.4203
3.0	.9681	.0319	27.0	.7471	.2529	51.0	.5766	.4234
3.5	.9629	.0371	27.5	.7431	.2569	51.5	.5735	.4265
4.0	.9577	.0423	28.0	.7391	.2609	52.0	.5704	.4296
4.5	.9526	.0474	28.5	.7351	.2649	52.5	.5673	.4327
5.0	.9474	.0526	29.0	.7311	.2689	53.0	.5642	.4358
5.5	.9423	.0577	29.5	.7272	.2728	53.5	.5612	.4388
6.0	.9373	.0627	30.0	.7233	.2767	54.0	.5582	.4418
6.5	.9322	.0678	30.5	.7194	.2806	54.5	.5552	.4448
7.0	.9272	.0728	31.0	.7155	.2845	55.0	.5522	.4478
7.5	.9222	.0778	31.5	.7117	.2883	55.5	.5492	.4508
8.0	.9172	.0828	32.0	.7078	.2922	56.0	.5462	.4538
8.5	.9123	.0877	32.5	.7040	.2960	56.5	.5433	.4567
9.0	.9074	.0926	33.0	.7002	.2998	57.0	.5404	.4596
9.5	.9025	.0975	33.5	.6965	.3035	57.5	.5375	.4625
10.0	.8976	.1024	34.0	.6927	.3073	58.0	.5346	.4654
10.5	.8928	.1072	34.5	.6890	.3110	58.5	.5317	.4683
11.0	.8880	.1120	35.0	.6853	.3147	59.0	.5288	.4712
11.5	.8832	.1168	35.5	.6816	.3184	59.5	.5260	.4740
12.0	.8785	.1215	36.0	.6779	.3221	60.0	.5232	.4768
12.5	.8737	.1263	36.5	.6743	.3257	60.5	.5203	.4797
13.0	.8690	.1310	37.0	.6706	.3294	61.0	.5175	.4825
13.5	.8644	.1356	37.5	.6670	.3330	61.5	.5148	.4852
14.0	.8597	.1403	38.0	.6634	.3366	62.0	.5120	.4880
14.5	.8551	.1449	38.5	.6599	.3401	62.5	.5092	.4908
15.0	.8505	.1495	39.0	.6563	.3437	63.0	.5065	.4935
15.5	.8459	.1541	39.5	.6528	.3472	63.5	.5038	.4962
16.0	.8413	.1587	40.0	.6493	.3507	64.0	.5010	.4990
16.5	.8368	.1632	40.5	.6458	.3542	64.5	.4983	.5017
17.0	.8323	.1677	41.0	.6423	.3577	65.0	.4957	.5043
17.5	.8278	.1722	41.5	.6388	.3612	65.5	.4930	.5070
18.0	.8234	.1766	42.0	.6354	.3646	66.0	.4903	.5097
18.5	.8189	.1811	42.5	.6320	.3680	66.5	.4877	.5123
19.0	.8145	.1855	43.0	.6286	.3714	67.0	.4851	.5149
19.5	.8101	.1899	43.5	.6252	.3748	67.5	.4825	.5175
20.0	.8058	.1942	44.0	.6219	.3781	68.0	.4799	.5201
20.5	.8014	.1986	44.5	.6185	.3815	68.5	.4773	.5227
21.0	.7971	.2029	45.0	.6151	.3849	69.0	.4747	.5253
21.5	.7928	.2072	45.5	.6118	.3882	69.5	.4722	.5278
22.0	.7885	.2115	46.0	.6085	.3915	70.0	.4696	.5304
22.5	.7843	.2157	46.5	.6053	.3947	70.5	.4671	.5329
23.0	.7801	.2199	47.0	.6020	.3980	71.0	.4646	.5354
23.5	.7759	.2241	47.5	.5988	.4012	71.5	.4621	.5379

APPENDIX C. YTTRIUM-90 INGROWTH FACTORS (0-27 DAYS)

t (days)	$1-e^{-\lambda t}$	t (days)	$1-e^{-\lambda t}$	t (days)	$1-e^{-\lambda t}$
0.00	.0000	9.00	.9029	18.00	.9906
0.25	.0627	9.25	.9090	18.25	.9912
0.50	.1215	9.50	.9147	18.50	.9917
0.75	.1766	9.75	.9201	18.75	.9922
1.00	.2283	10.00	.9251	19.00	.9927
1.25	.2767	10.25	.9298	19.25	.9932
1.50	.3221	10.50	.9342	19.50	.9936
1.75	.3646	10.75	.9384	19.75	.9940
2.00	.4045	11.00	.9422	20.00	.9944
2.25	.4418	11.25	.9458	20.25	.9948
2.50	.4768	11.50	.9492	20.50	.9951
2.75	.5097	11.75	.9524	20.75	.9954
3.00	.5404	12.00	.9554	21.00	.9957
3.25	.5692	12.25	.9582	21.25	.9959
3.50	.5963	12.50	.9608	21.50	.9962
3.75	.6216	12.75	.9633	21.75	.9964
4.00	.6453	13.00	.9656	22.00	.9967
4.25	.6676	13.25	.9678	22.25	.9969
4.50	.6884	13.50	.9697	22.50	.9971
4.75	.7080	13.75	.9716	22.75	.9973
5.00	.7263	14.00	.9734	23.00	.9974
5.25	.7435	14.25	.9751	23.25	.9976
5.50	.7596	14.50	.9766	23.50	.9977
5.75	.7746	14.75	.9781	23.75	.9979
6.00	.7888	15.00	.9795	24.00	.9980
6.25	.8020	15.25	.9808	24.25	.9981
6.50	.8145	15.50	.9820	24.50	.9982
6.75	.8261	15.75	.9831	24.75	.9984
7.00	.8370	16.00	.9842	25.00	.9985
7.25	.8472	16.25	.9852	25.25	.9986
7.50	.8568	16.50	.9861	25.50	.9987
7.75	.8658	16.75	.9870	25.75	.9987
8.00	.8742	17.00	.9878	26.00	.9988
8.25	.8820	17.25	.9886	26.25	.9989
8.50	.8896	17.50	.9893	26.50	.9990
8.75	.8864	17.75	.9900	26.75	.9990
				27.00	.9991

APPENDIX D. STRONTIUM-89 DECAY FACTORS (0-59.5 DAYS)($t_{½}$ = 51 DAYS)

t (days)	$e^{-\lambda t}$	t (days)	$e^{-\lambda t}$	t (days)	$e^{-\lambda t}$
0.0	1.0000	20.0	.7620	40.0	.5808
0.5	.9932	20.5	.7569	40.5	.5769
1.0	.9865	21.0	.7518	41.0	.5730
1.5	.9798	21.5	.7568	41.5	.5690
2.0	.9732	22.0	.7416	42.0	.5652
2.5	.9668	22.5	.7366	42.5	.5613
3.0	.9601	23.0	.7317	43.0	.5575
3.5	.9536	23.5	.7267	43.5	.5539
4.0	.9471	24.0	.7218	44.0	.5500
4.5	.9407	24.5	.7169	44.5	.5462
5.0	.9344	25.0	.7120	45.0	.5427
5.5	.9280	25.5	.7072	45.5	.5380
6.0	.9217	26.0	.7023	46.0	.5352
6.5	.9155	26.5	.6977	46.5	.5318
7.0	.9093	27.0	.6930	47.0	.5280
7.5	.9031	27.5	.6882	47.5	.5245
8.0	.8970	28.0	.6836	48.0	.5210
8.5	.8909	28.5	.6790	48.5	.5175
9.0	.8849	29.0	.6742	49.0	.5140
9.5	.8789	29.5	.6699	49.5	.5105
10.0	.8729	30.0	.6651	50.0	.5070
10.5	.8670	30.5	.6608	50.5	.5035
11.0	.8612	31.0	.6562	51.0	.5000
11.5	.8553	31.5	.6519	51.5	.4967
12.0	.8495	32.0	.6473	52.0	.4933
12.5	.8438	32.5	.6430	52.5	.4900
13.0	.8381	33.0	.6388	53.0	.4868
13.5	.8324	33.5	.6342	53.5	.4834
14.0	.8268	34.0	.6300	54.0	.4801
14.5	.8212	34.5	.6259	54.5	.4769
15.0	.8156	35.0	.6215	55.0	.4734
15.5	.8101	35.5	.6172	55.5	.4702
16.0	.8046	36.0	.6131	56.0	.4671
16.5	.7992	36.5	.6090	56.5	.4640
17.0	.7938	37.0	.6050	57.0	.4608
17.5	.7883	37.5	.6009	57.5	.4578
18.0	.7881	38.0	.5968	58.0	.4547
18.5	.7778	38.5	.5928	58.5	.4513
19.0	.7725	39.0	.5888	59.0	.4484
19.5	.7672	39.5	.5848	59.5	.4454